N-Z00/165

4

Intellectual Property Office
of New Zealand

PRIORITY DOCUMENT
SUBMITTED OR TRANSMITTED IN
COMPLIANCE WITH
RULE 17.1(a) OR (b)

CERTIFICATE

This certificate is issued in support of an application for Patent registration in a country outside New Zealand pursuant to the Patents Act 1953 and the Regulations thereunder.

I hereby certify that annexed is a true copy of the Provisional Specification as filed on 19 October 1999 with an application for Letters Patent number 500519 made by FISHER & PAYKEL LIMITED.

Dated 3 July 2000.

Neville Harris

Neville Harris
Commissioner of Patents

500519

NEW ZEALAND

PATENTS ACT, 1953

PROVISIONAL SPECIFICATION

"Free Piston Compressor Stroke Control"

We, FISHER & PAYKEL LIMITED, a company duly incorporated under the laws of New Zealand of 78 Springs Road, East Tamaki, Auckland, New Zealand, do hereby declare this invention to be described in the following statement:

BACKGROUND

(A) FIELD OF THE INVENTION

This invention relates to free piston compressors (also called vibrating and linear compressors) for vapour compression refrigeration systems and in particular a control system to prevent failure or damage due to unwanted changes of compression level caused by changes to ambient temperature or operating conditions of the refrigeration system.

(B) PRIOR ART

Linear reciprocating motors obviate the need for crank mechanisms which characterise compressors powered by rotating electric motors and which produce high side forces requiring oil lubrication. Such a motor is described in US 4,602,174.

The piston of a free piston compressor oscillates in conjunction with a spring as a resonant system and there are no inherent limits to the amplitude of oscillation except for collision with a stationary part, typically part of the cylinder head assembly. The piston will take up an average position and amplitude that depend on gas forces and input electrical power. Therefore for any given input electrical power, as either evaporating or condensing pressure reduces, the amplitude of oscillation increases until collision occurs. It is therefore necessary to limit the power as a function of these pressures.

Various methods have been used to limit oscillation amplitude including secondary gas spring, piston position detection, piston position calculation based on current and applied voltage (US 5,496,153) measuring ambient and/or evaporating temperature (US 4,179,899, US 4,283,920). Each of these methods requires the cost of additional sensors or has some performance limitation.

It is desirable for maximum efficiency to operate free piston refrigeration compressors at the natural frequency of the mechanical system. This frequency is determined by the spring constant and mass of the mechanical system and also by the elasticity coefficient of the refrigerant gas. The elasticity coefficient of the gas increases with both evaporating and condensing pressures. Consequently the natural frequency also increases. Therefore for best operation the frequency of the electrical system powering the compressor needs to vary to match the mechanical system frequency as it varies.

Methods of synchronising the electrical voltage applied to the compressor motor windings with the mechanical system frequency are well known. For a permanent magnet motor used in a free piston compressor, a back electromotive force (back EMF) is induced in the motor windings proportional to the piston velocity as shown in Fig 1. The equivalent circuit of the motor is shown in Fig 2. An alternating voltage (V) is applied in synchronism with the alternating EMF (αv) in order to power the compressor. US

4,320,448 (Okuda et al.) discloses a method whereby the timing of the applied voltage is determined by detecting the zero crossings of the motor back EMF. The application of alternating voltage to the motor winding is controlled to avoid the time at which the EMF intersects with the zero level to allow back EMF zero crossing detection.

US 4,320,448 also discloses a method of adjusting the power to the compressor in accordance with ambient temperature of the refrigerating device and/or the evaporator temperature so as to prevent damage to the compressor. US 4,320,448 discloses the use of a dedicated temperature sensor to measure ambient temperature.

SUMMARY OF THE INVENTION

It is the object of this invention to provide an alternative means to limit stroke control without the need for additional measurement means and without limitation of performance by recognising that variation of the natural frequency with changes of evaporating and condensing pressures can also be used in conjunction with measurement of evaporating temperature to limit power to the compressor to prevent unwanted damage to the compressor.

Accordingly in one aspect the invention may broadly be said to consist in a method for driving and controlling the amplitude of the piston in a free piston vapour compressor wherein said piston is spring mounted and reciprocates in a cylinder and wherein the vibrating system of piston, spring and the pressure of said vapour has a resonant frequency which varies with vapour pressure, said method using a linear brushless DC motor having at least one winding and comprising the steps of:

electronically commutating said at least one winding from a DC supply to reciprocate said piston, unpowering said at least one winding at various intervals and detecting zero-crossings of the back EMF induced in said at least one winding, using the zero-crossing timing information to initiate commutation of said at least one winding to thereby drive said piston at the resonant frequency of said vibrating system, measuring said resonant frequency and the evaporating temperature of the vapour entering the compressor, limiting the maximum current in said at least one winding by limiting the value of a parameter which determines current supply during commutation to a selected maximum current commutation value in a selected one of a set of look up tables containing maximum current commutation values for each of a plurality of resonant frequencies for said vibrating system and selecting the value which corresponds to the measured resonant frequency, each look up table corresponding to a non-overlapping range of evaporation temperatures of vapour entering the compressor and being selected on the basis of said measured evaporation temperature.

Preferably, said parameter which is limited is the magnitude of the current and said look up tables store maximum current values.

Preferably, parameter which is limited is the duration of commutation and said look up tables store maximum commutation duration values.

In a further aspect the invention may broadly be said to consist in a free piston vapour compressor comprising:

a piston,

a cylinder,

said piston being spring mounted and reciprocable within said cylinder, the vibrating system of piston, spring and the pressure of said vapour having a resonant frequency which varies with vapour pressure,

a linear brushless DC motor drivably coupled to said piston having at least one winding,

a DC power supply,

means for electronically commutating said at least one winding from said DC supply to reciprocate said piston,

means for sampling the back EMF induced in said at least one winding when commutation current is not flowing and for detecting back EMF zero-crossings and producing timing signals derived therefrom,

means which initiate commutation of said at least one winding in response to the zero-crossing timing signals to thereby drive said piston at the resonant frequency of said vibrating system,

and means for measuring said resonant frequency,

a temperature sensor for sensing the evaporation temperature of the vapour entering the compressor,

means for controlling said commutation means which determine the duration current is supplied by said commutation means to thereby limit the amplitude of reciprocation of said piston,

a memory which stores a set of look up tables containing maximum current commutation values for each of a plurality of resonant frequencies for said vibrating system, each look up table corresponding to a non-overlapping range of evaporation temperatures of vapour entering the compressor, means for selecting a look up table to use on the basis of said measured evaporation temperature,

and means for selecting the value in said selected table which corresponds to the measured resonant frequency and for supplying same to said commutation controlling means.

Preferabl_ _neans for measuring the current fl_ _ng in said at least one winding during commutation, wherein said look up tables store maximum current values and said commutation controlling means terminate commutation when the magnitude of measured current reaches the maximum current value selected from said look up table.

Preferably, said look up tables store maximum commutation duration values and said commutation controlling means set the maximum commutation time as that selected from said look up table.

In a still further aspect the invention may broadly be said to consist in a method for driving and controlling the amplitude of the piston in a free piston vapour compressor wherein said piston is spring mounted and reciprocates in a cylinder and wherein the vibrating system of piston, spring and the pressure of said vapour has a resonant frequency which varies with vapour pressure, said method using a linear brushless DC motor having at least one winding and comprising the steps of:

electronically commutating said at least one winding from a DC supply to reciprocate said piston, unpowering said at least one winding at various intervals and detecting zero-crossings of the back EMF induced in said at least one winding, using the zero-crossing timing information to initiate commutation of said at least one winding to thereby drive said piston at the resonant frequency of said vibrating system, measuring said resonant frequency and a property of the vapour entering the compressor which is an indicator of the pressure on evaporation, limiting the maximum current in said at least one winding by limiting the value of a parameter which determines current supply during commutation to a maximum current commutation value calculated as a function of said measured resonant frequency and said measured property.

In a still further aspect the invention may broadly be said to consist in a free piston vapour compressor comprising:

a piston,

a cylinder,

said piston being spring mounted and reciprocable within said cylinder, the vibrating system of piston, spring and the pressure of said vapour having a resonant frequency which varies with vapour pressure,

a linear brushless DC motor drivably coupled to said piston having at least one winding,

a DC power supply,

means for electronically commutating said at least one winding from said DC supply to reciprocate said piston,

means for sampling the back EMF induced in said at least one winding when commutation current is not flowing and for detecting back EMF zero-crossings and

producing timing signals derived therefrom,

means which initiate commutation of said at least one winding in response to the zero-crossing timing signals to thereby drive said piston at the resonant frequency of said vibrating system,

and means for measuring said resonant frequency,

a sensor for measuring a property of the vapour entering the compressor which is an indicator of the pressure on evaporation,

means for controlling said commutation means which determine the duration current is supplied by said commutation means to thereby limit the amplitude of reciprocation of said piston,

a processor for calculating as a function of said measured resonant frequency and said measured property the maximum current commutation value and supplying same to said commutation controlling means.

The "evaporating temperature of the vapour entering the compressor" is also referred to in this specification as the "evaporator temperature". Likewise the "resonant frequency" is also referred to as the "natural frequency".

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows motor piston displacement and back EMF waveforms for a free piston compressor motor;

Figure 2 shows an equivalent circuit for such a motor;

Figure 3 shows an inverter for electronically commutating a single phase free piston motor;

Figure 4 shows graphs of maximum motor current as a function of frequency and evaporation temperature for a motor of the present invention;

Figure 5 is a block diagram of the motor control circuit;

Figure 6 is a graph of RMS motor current versus motor winding current decay time;

Figure 7 is a flow chart of the motor control timing program;

Figure 8 is a flow chart of commutation time determination using evaporator temperature and stroke time data; and

Figure 9 shows motor piston displacement and motor current waveforms.

DESCRIPTION OF THE PREFERRED EMBODIMENTS OF THE INVENTION

Experiments have established that a free piston compressor is most efficient when driven at the natural frequency of the compressor piston-spring system. However as well as any deliberately provided metal spring, there is an inherent gases spring, the effective

spring constant which varies as either evaporator or condenser pressure varies. In order to provide a motor which can vary its drive frequency to match the changes in the compressor natural frequency it is proposed to use an electronically commutated permanent magnet motor. This derives from the applicant's experience in electronically commutated permanent magnet motors as disclosed in US 4857814 and WO 98/35428 for example. Those references disclose the control of a 3 phase rotating motor, but the same control principles can be applied to linear motors. A suitable linear motor need only be a single phase device and a suitable inverter bridge circuit for powering a motor can be of the simple form shown in Figure 3.

By monitoring back EMF zero crossings in the motor winding current commutation can be determined to follow the natural frequency of the piston. Since there is only a single winding, the current flowing through either upper or lower inverter switching devices 11 or 12 must be interrupted so that back EMF can be measured. Controlling the current through the motor winding in accordance with detected back EMF ensures current and back EMF are maintained in phase for maximum motor efficiency.

The frequency of operation of the motor is effectively continuously monitored as frequency is twice the reciprocal of the time between back EMF zero crossings. Furthermore according to WO 98/35428 the current decay time through free wheel diodes 13 and 14 after commutation has ceased is directed proportional to the motor current and thus a measure of motor current is available.

The maximum motor current that can be employed before the piston collides with the cylinder head of the compressor varies depending upon the evaporator temperature and the natural frequency of the vibrating system

Figure 4 shows graphs of maximum permitted motor current against natural mechanical system frequency and condenser temperatures for different evaporating temperatures. These show the dependence of maximum motor current on both these variables. They also demonstrate that condenser temperatures are proportional to mechanical system frequency and thus maximum current control can be achieved without the need for measurement of the third variable, condenser temperature.

The motor control circuit according to this invention is shown in Figure 5. It utilises the observation that mechanical system frequency is related to condenser temperature. In this invention the back EMF signal induced in the motor windings 1 is sensed and digitised by circuit 2 and applied to the input of a microcomputer 3 which computes the appropriate timing for the commutation of current to the motor windings to ensure that the current is in phase with the back EMF. These commutation timing signals switch an inverter 4 (as shown in Figure 3) which delivers current to the motor windings 1. The microcomputer 3 also measures the time between back EMF zero crossings and

thereby the period of the EMF waveform. The natural oscillation frequency of the mechanical system is the inverse of the period of the EMF waveform. The microcomputer 3 therefore has a measure of this frequency at all times.

The conventional temperature sensor 5 for measuring the evaporator temperature for defrost purposes is utilised and its output is digitised and supplied as a further input to microcomputer 3.

According to the present invention one method of limiting maximum motor current and thus maximum displacement of the piston is for the microcomputer 3 to calculate a maximum current amplitude for each half cycle of piston oscillation and limit the actual current amplitude to less than the maximum. WO 98/35428 discloses a method of measuring motor current in an electronically commutated permanent magnet motor by utilising the digitised back EMF signal in an unpowered winding to measure the time taken for the current in the motor winding to decay to zero. Use of this technique in the present invention enables microcomputer 3 to limit maximum power without the need for dedicated current sensing or limiting circuitry. The RMS motor current is directly proportional to the time duration of current decay through the "freewheeling" diodes 13 or 14 after the associated inverter switching device has switched off. The current decay results of course from the motor winding being an inductor which has stored energy during commutation and which must be dissipated after commutation has ceased. A graph of RMS motor current against current decay duration (which is a simplification of Figure 6 in WO 98/35428) is shown in Figure 6.

Another preferred method is to limit the time that the current is commutated on instead of limiting the maximum current value. Fig 9 shows the current waveform under such control. This is in effect pulse width modulation (PWM) with only one modulated current pulse per commutation interval. With this method a delay time from the back EMF zero crossing is computed to minimise the phase angle between the Motor Current and the back EMF for maximum efficiency. The invertor switch supplying current is turned off at a time in the motor half cycle to allow, after a current decay period, time to monitor zero crossing of the back EMF to determine the start commutation for the next half cycle. The commutation time is also compared with a maximum commutation time appropriate to the motor frequency and evaporator temperature to ensure maximum amplitude of the piston stroke is not exceeded.

A flow diagram of the microcomputer control strategy to implement this method is shown in Figures 7 and 8. Referring to Figure 7 when the compressor is first powered (21), or is powered after sufficient time delay to ensure pressures are equalised in the refrigeration system, the compressor runs at a minimum frequency. The stroke period of this minimum frequency is measured as Run_Stroke and shown in the microcomputer

as Low_Stroke and a minimum Commutation Time is set for this value (28). For each subsequent stroke the stroke period is measured and defined as the parameter Run_Stroke (24). The difference between Run_Stroke and Low_Stroke is computed (31, Figure 8). This difference is called Period_Index. The Period_Index is used in this sub-routine as an index pointer in a lookup table of maximum commutation times for different stroke times (frequencies). This table is called the Pulse_Limit_Value Table. In this instance there are 7 lookup tables (33 to 39) corresponding to 7 ranges of Evaporating Temperature (40 to 65).

The motor control circuit is typically included in a Temperature Control loop in the conventional manner in order to maintain the temperature of the enclosed refrigerated space of the refrigeration system. This control loop will be setting desired values for the power to be applied to the motor windings depending on the operating conditions of the refrigeration system. These values of desired power will correspond to values of commutation time. These values of Commutation Time are compared on a stroke by stroke basis with the Pulse_Limit_Value (40, Figure 8). If the Desired value of commutation time is greater than the Pulse_Limit_Value then the commutation time is limited to the Pulse_Limit_Value. This value sets the Commutation Timer (25) which controls the ON period of the relevant inverter switching device. As previously explained, Motor current can also be used in a similar manner to limit power applied to the motor to safe levels, but even where commutation time is being controlled it is desirable to measure motor current in the manner previously described and compare it with a stored absolute maximum value (26) which if exceeded will cause the microcomputer program to reset (27).

Of course other methods of determining maximum commutation time and/or maximum current value are feasible, for instance if the microcomputer is sufficiently powerful, for example recent advances in DSP chip technology, these values can be computed directly without the need for lookup tables.

If the DC power supply Voltage supplied to the inverter bridge of Fig 3 varies significantly this will result in variation of Motor Current for any given commutation time which should be allowed for. It may be desirable for maximum accuracy for the microprocessor to sense this and compensate accordingly.

PROVISIONALLY WHAT WE CLAIM IS:

1. A method for driving and controlling the amplitude of the piston in a free piston vapour compressor wherein said piston is spring mounted and reciprocates in a cylinder and wherein the vibrating system of piston, spring and the pressure of said vapour has a resonant frequency which varies with vapour pressure, said method using a linear brushless DC motor having at least one winding and comprising the steps of:

electronically commutating said at least one winding from a DC supply to reciprocate said piston, unpowering said at least one winding at various intervals and detecting zero-crossings of the back EMF induced in said at least one winding, using the zero-crossing timing information to initiate commutation of said at least one winding to thereby drive said piston at the resonant frequency of said vibrating system, measuring said resonant frequency and the evaporation temperature of the vapour entering the compressor, limiting the maximum current in said at least one winding by limiting the value of a parameter which determines current supply during commutation to a selected maximum current commutation value in a selected one of a set of look up tables containing maximum current commutation values for each of a plurality of resonant frequencies for said vibrating system and selecting the value which corresponds to the measured resonant frequency, each look up table corresponding to a non-overlapping range of evaporation temperatures of vapour entering the compressor and being selected on the basis of said measured evaporation temperature.

2. A method according to claim 1 wherein said parameter which is limited is the magnitude of the current and said look up tables store maximum current values.

3. A method according to claim 1 wherein parameter which is limited is the duration of commutation and said look up tables store maximum commutation duration values.

4. A free piston vapour compressor comprising:

a piston,

a cylinder,

said piston being spring mounted and reciprocable within said cylinder, the vibrating system of piston, spring and the pressure of said vapour having a resonant frequency which varies with vapour pressure,

a linear brushless DC motor drivably coupled to said piston having at least one winding,

a DC power supply,

means for electronically commutating said at least one winding from said DC supply to reciprocate said piston,

means for sampling the back EMF induced in said at least one winding when commutation current is not flowing and for detecting back EMF zero-crossings and producing timing signals derived therefrom,

means which initiate commutation of said at least one winding in response to the zero-crossing timing signals to thereby drive said piston at the resonant frequency of said vibrating system,

and means for measuring said resonant frequency,

a temperature sensor for sensing the evaporation temperature of the vapour entering the compressor,

means for controlling said commutation means which determine the duration current is supplied by said commutation means to thereby limit the amplitude of reciprocation of said piston,

a memory which stores a set of look up tables containing maximum current commutation values for each of a plurality of resonant frequencies for said vibrating system, each look up table corresponding to a non-overlapping range of evaporation temperatures of vapour entering the compressor, means for selecting a look up table to use on the basis of said measured evaporation temperature,

and means for selecting the value in said selected table which corresponds to the measured resonant frequency and for supplying same to said commutation controlling means.

5. A method according to claim 4 including means for measuring the current flowing in said at least one winding during commutation, wherein said look up tables store maximum current values and said commutation controlling means terminate commutation when the magnitude of measured current reaches the maximum current value selected from said look up table.

6. A method according to claim 4 wherein said look up tables store maximum commutation duration values and said commutation controlling means set the maximum commutation time as that selected from said look up table.

7. A method for driving and controlling the amplitude of the piston in a free piston vapour compressor wherein said piston is spring mounted and reciprocates in a cylinder and wherein the vibrating system of piston, spring and the pressure of said vapour has a resonant frequency which varies with vapour pressure, said method

using a linear brushless DC motor having at least one winding and comprising the steps of:

electronically commutating said at least one winding from a DC supply to reciprocate said piston, unpowering said at least one winding at various intervals and detecting zero-crossings of the back EMF induced in said at least one winding, using the zero-crossing timing information to initiate commutation of said at least one winding to thereby drive said piston at the resonant frequency of said vibrating system, measuring said resonant frequency and a property of the vapour entering the compressor which is an indicator of the pressure on evaporation, limiting the maximum current in said at least one winding by limiting the value of a parameter which determines current supply during commutation to a maximum current commutation value calculated as a function of said measured resonant frequency and said measured property.

8. A free piston vapour compressor comprising:

a piston,

a cylinder,

said piston being spring mounted and reciprocable within said cylinder, the vibrating system of piston, spring and the pressure of said vapour having a resonant frequency which varies with vapour pressure,

a linear brushless DC motor drivably coupled to said piston having at least one winding,

a DC power supply,

means for electronically commutating said at least one winding from said DC supply to reciprocate said piston,

means for sampling the back EMF induced in said at least one winding when commutation current is not flowing and for detecting back EMF zero-crossings and producing timing signals derived therefrom,

means which initiate commutation of said at least one winding in response to the zero-crossing timing signals to thereby drive said piston at the resonant frequency of said vibrating system,

and means for measuring said resonant frequency,

a sensor for measuring a property of the vapour entering the compressor which is an indicator of the pressure on evaporation,

means for controlling said commutation means which determine the duration current is supplied by said commutation means to thereby limit the amplitude of reciprocation of said piston,

a processor for calculating as a function of said measured resonant frequency and

said measured property the maximum current commutation value and supplying same to said commutation controlling means.

DATED THIS 19th DAY OF October 1999
A.J. PARK & SON
PER Tabatha O'Leary
AGENTS FOR THE APPLICANT

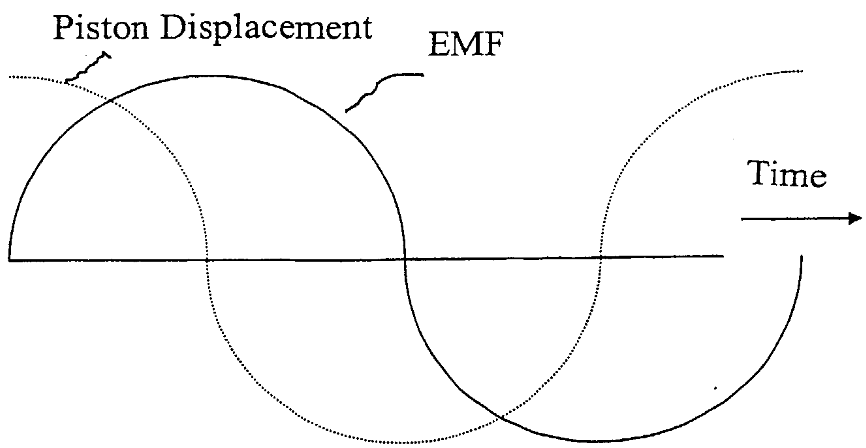

Fig 1: Motor EMF and Displacement Waveforms

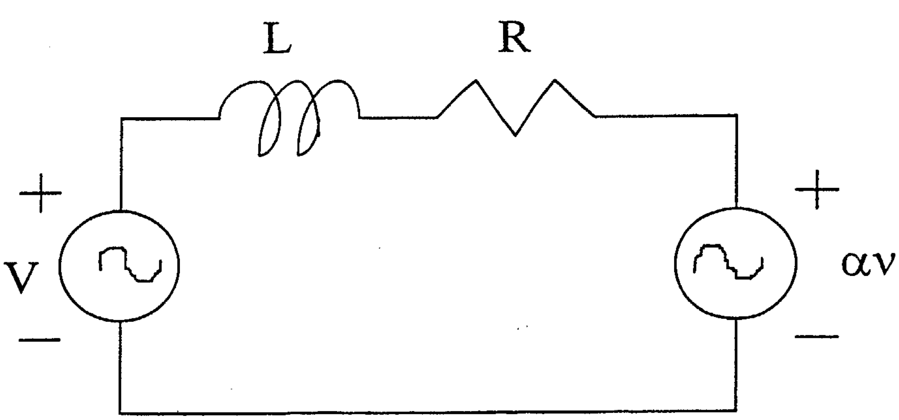

Fig 2: Motor Equivalent Circuit

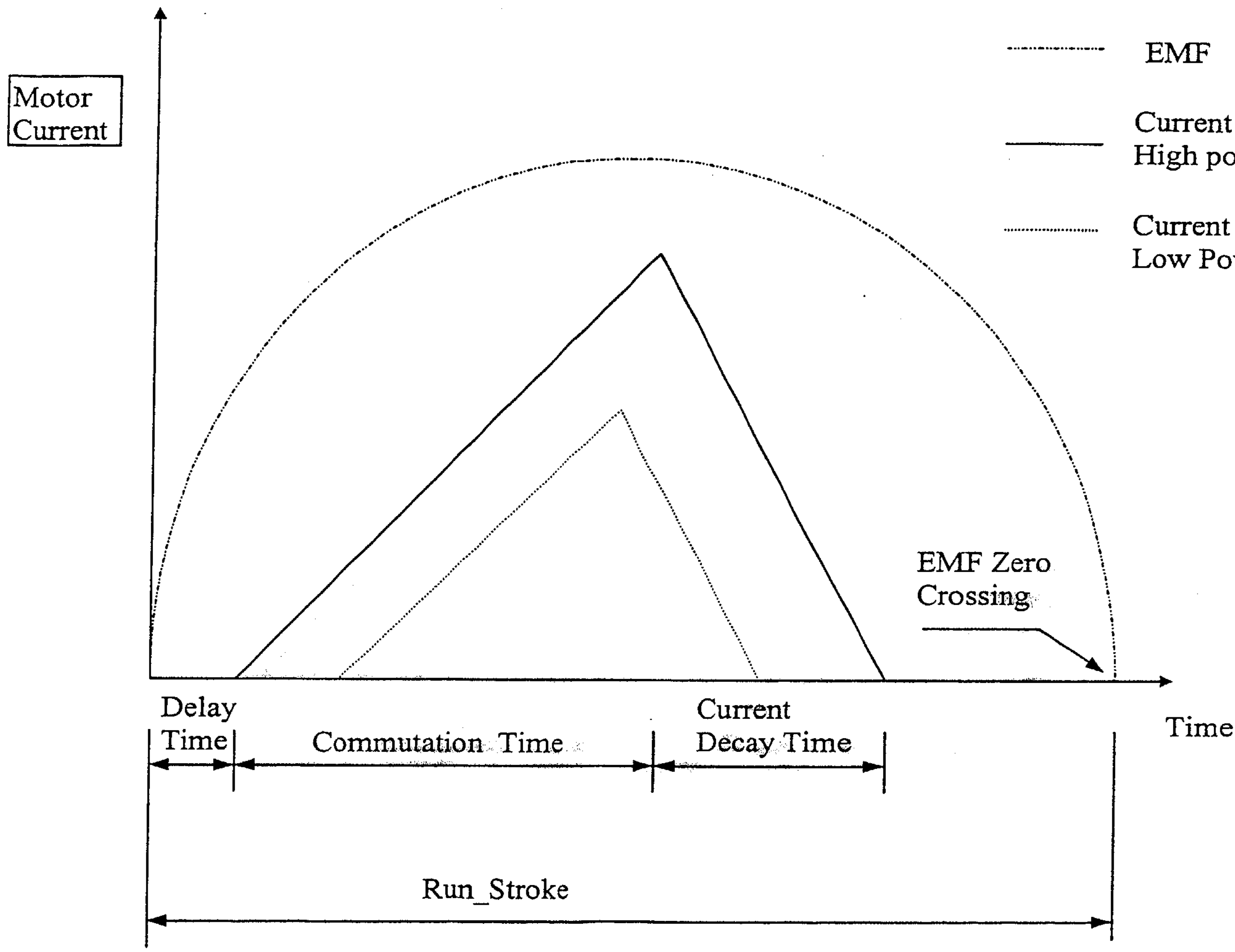

Fig 9: Motor Current Waveform and Timing

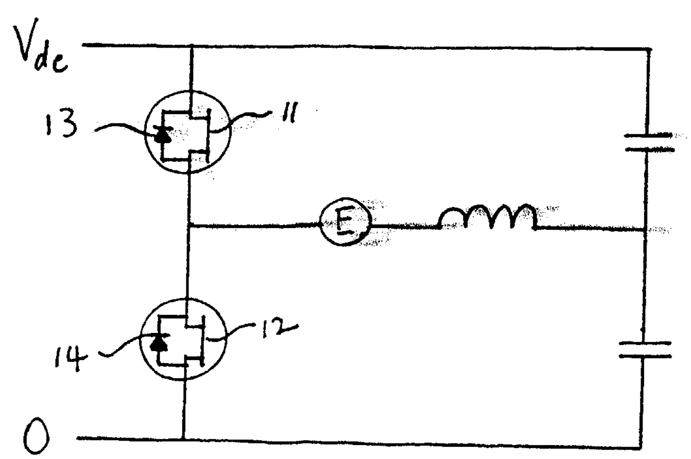

Fig 3

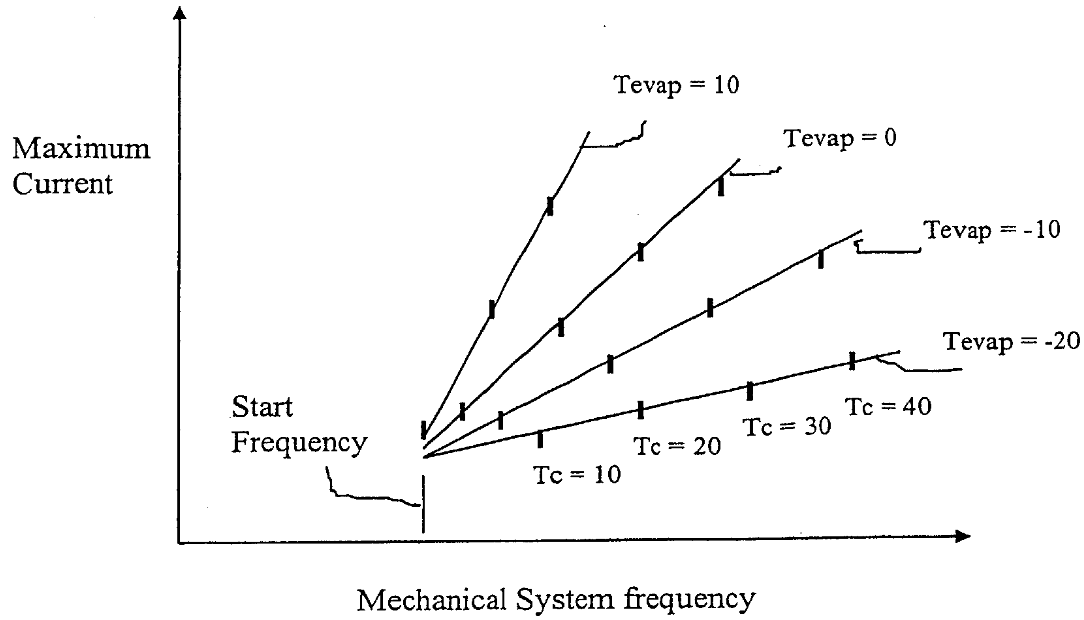

Fig 4: Maximum Current as a function of Evaporating Temperature and Frequency

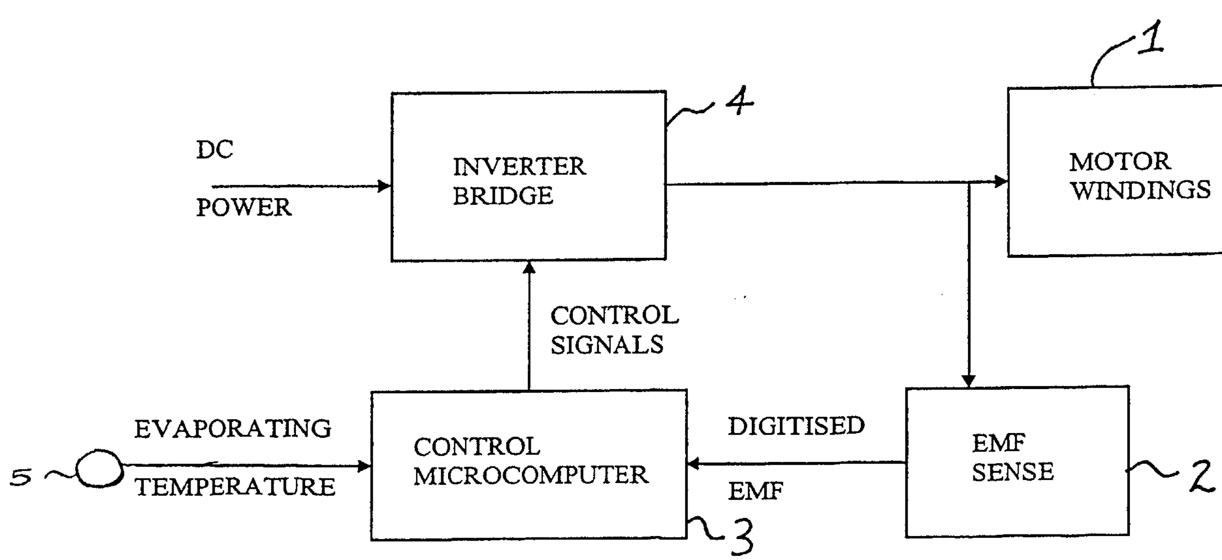

Fig 5: Block diagram of the motor control circuit

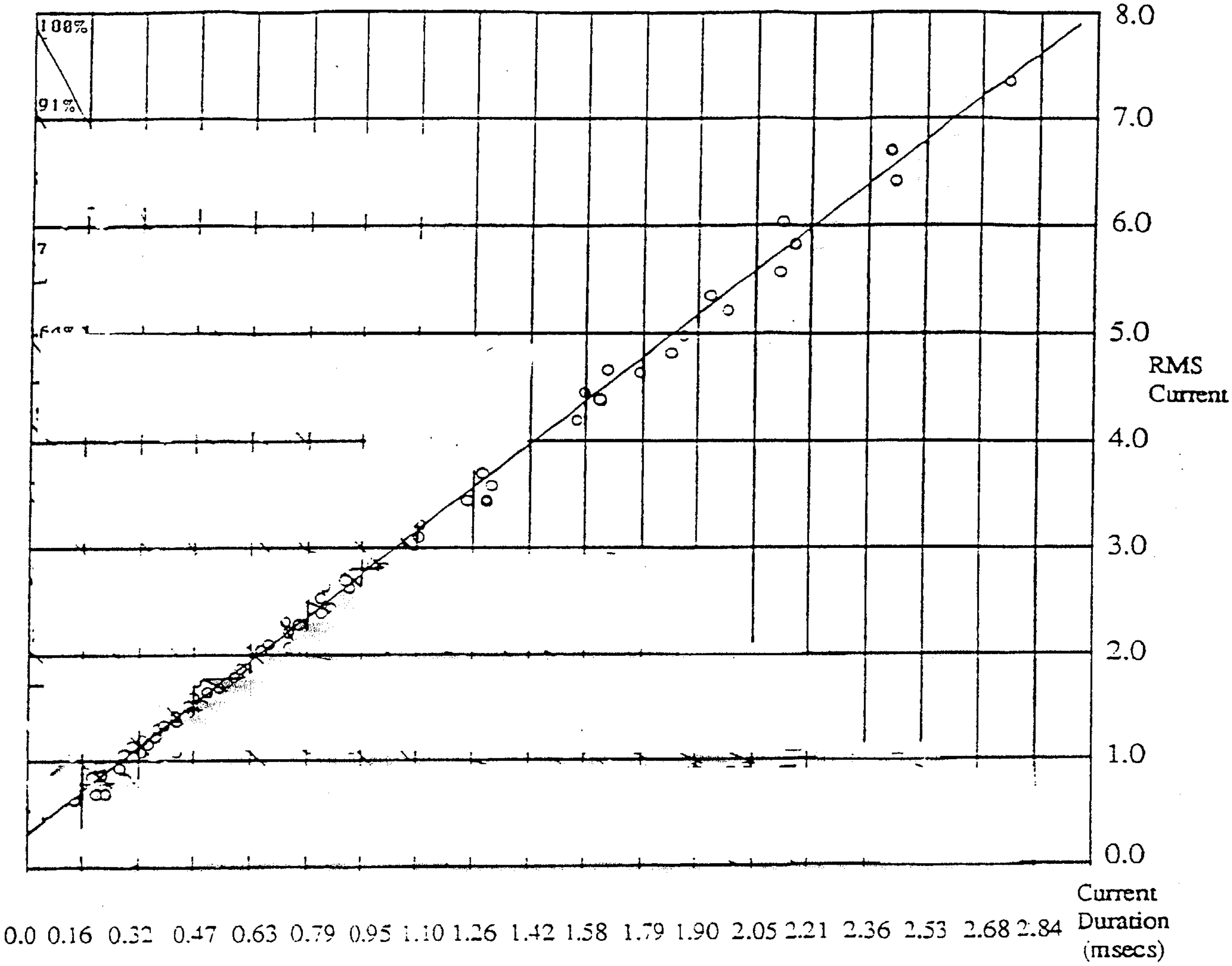
100%
91%
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
RMS Current
0.0 0.16 0.32 0.47 0.63 0.79 0.95 1.10 1.26 1.42 1.58 1.79 1.90 2.05 2.21 2.36 2.53 2.68 2.84
Current Duration (msecs)

Fig 6

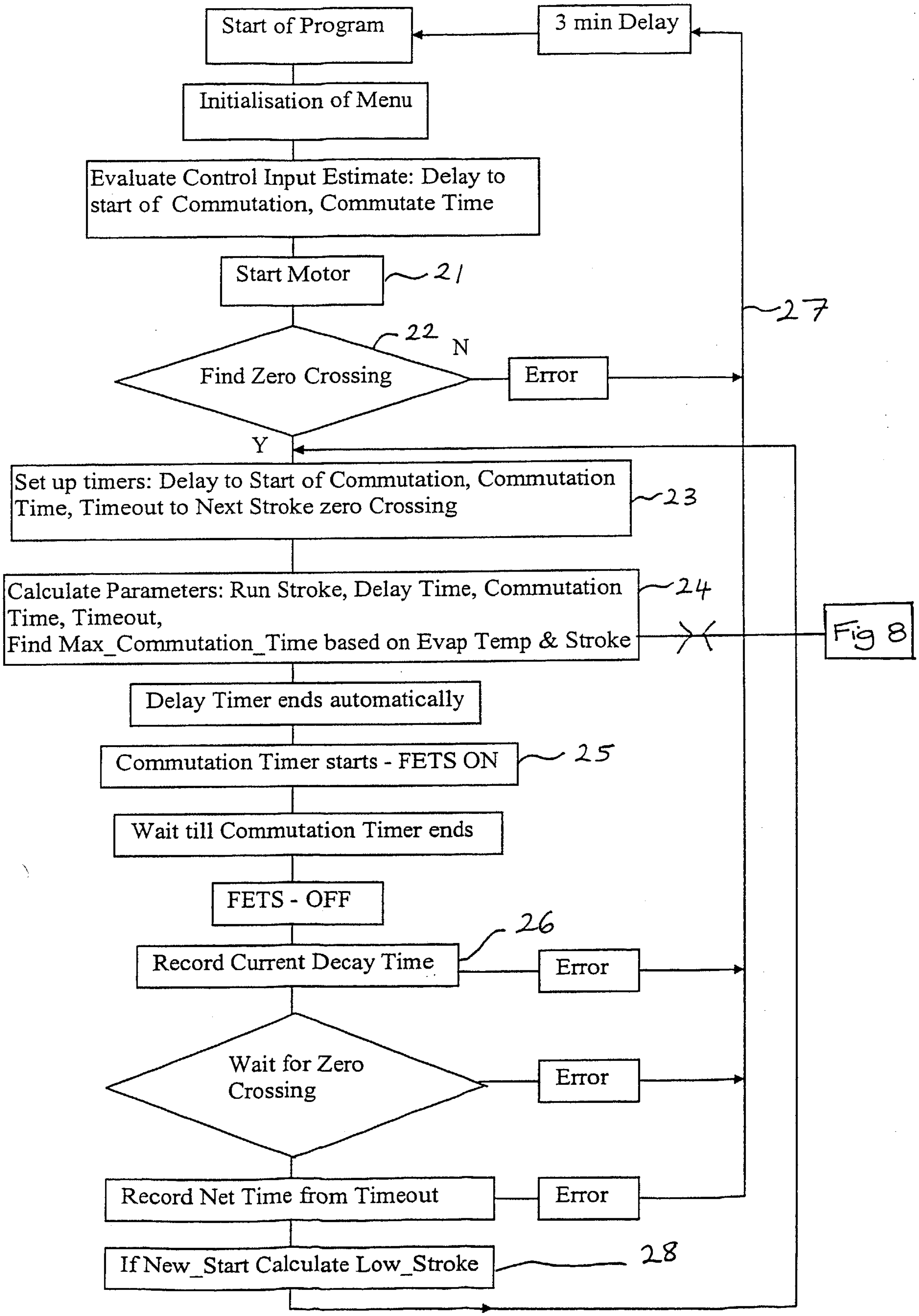

Fig 7: Control Microcomputer Motor Control Timing Flow chart